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RESEARCH MEMORANDUM

EXPERIMENTAL ROCKET PERFORMANCE WITH 15 PERCENT FLUORINE - 85 PERCENT OXYGEN AND JP-4

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August 29, 1955

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RESEARCH MEMORANDUM

EXPERIMENTAL ROCKET PERFORMANCE WITH 15 PERCENT FLUORINE - 85 PERCENT OXYGEN AND JP-4

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SUMMARY

Experimental performance of a rocket engine using 15 percent fluorine - 85 percent oxygen and JP-4 was compared with that obtained using oxygen and JP-4. The regeneratively cooled engine was operated at 5000 pounds thrust and a chamber pressure of 350 pounds per square inch absolute.

The peak specific impulse with 15 percent fluorine was 251 pound-seconds per pound. This is an increase of 3.3 percent over the 243 pound-seconds per pound obtained without fluorine. Each of these values is 92 percent of the respective theoretical maximum for equilibrium composition expansion.

Regenerative cooling of the engine was adequate in spite of the added fluorine. However, heat rejection at peak performance increased 24 percent from about 0.45 Btu/(sq in.)(sec) without fluorine (obtained elsewhere) to 0.56 Btu/(sq in.)(sec) with fluorine (obtained in this investigation).

INTRODUCTION

This investigation was conducted to determine the increase in specific impulse and heat rejection obtained by adding 15 percent fluorine to oxygen in an oxygen - JP-4 engine.

The liquid oxygen - jet fuel propellant combination is under active development for long-range missiles because of its desirable handling and logistic properties. The range of long-range ballistic missiles may be increased substantially with relatively small increases in specific impulse.

One way of increasing specific impulse without major changes to an oxygen - jet fuel thrust chamber is to add fluorine to the oxygen. Theoretical calculations (ref. 1) indicate an increase in specific impulse with up to 70 percent fluorine in the oxidant. These calculations and experimental studies (ref. 2) show that specific impulse may be increased approximately 1 percent for each 5 percent fluorine added up to 30 percent fluorine. Reference 3 shows that more than about 5 percent fluorine in oxygen is self-igniting with jet fuel. However, heat-rejection and material-durability problems increase rapidly with fluorine addition.

The engine used in the experiments reported herein was a commercially developed 5500-pound-thrust unit suitable for oxygen and jet fuel (ref. 4). An analysis of its cooling capacity was made prior to testing. It showed that the engine should cool adequately with up to 23 percent fluorine over the oxidant-fuel-ratio range investigated. Fifteen percent fluorine was chosen for this investigation, since this percentage should give a definite increase in performance with a reasonable chance of avoiding engine failure.

The experiments reported herein were made at a chamber pressure of 350 pounds per square inch absolute. JP-4 was used with oxygen alone and with 15 percent fluorine - 85 percent oxygen. Experimental values of specific impulse and heat rejection for various oxidant-fuel ratios are presented for both oxidants with JP-4.

APPARATUS

Propellants and Flow System

The fuel used was JP-4. Its properties are presented in table I. Silicone oil was added to reduce heat transfer to the engine walls as was done by the manufacturer (ref. 4). Oxygen was obtained as a liquid and contained no more than 0.5 percent impurities. Fluorine of 98 percent purity was obtained as a gas in commercial cylinders. The propellants were fed to the engine from helium pressurized tanks; the flow rates were controlled by varying tank pressures.

Engine

The thrust chamber (fig. 1) was a commercial unit designed for 5500 pounds thrust at chamber pressure of 400 pounds per square inch absolute. It was originally intended for use with liquid oxygen and ethyl alcohol, but was later used by the manufacturer with aviation gasoline and jet fuel. Regenerative cooling was accomplished by flowing the fuel through spiral passages surrounding the combustion chamber.

The injector (fig. 2) consisted of alternate rings of fuel and oxidant like-on-like sets of two holes each. It had 97 fuel sets with each hole 0.046 inch in diameter. There were 82 oxidant sets of 0.055-inch-diameter holes. In addition, there were 30 single fuel holes of 0.029-inch diameter in the outside ring.

Instrumentation

The engine was mounted on a horizontal flexure plate stand. Thrust was measured with a calibrated strain gage and recorded on an oscillograph. The probable error was approximately ±1.5 percent.

Both fuel and oxidant flows were measured with turbine-type flowmeters, which recorded on an oscillograph. The probable error of these measurements including density determination was approximately ±1.5 percent.

Combustion-chamber pressure was measured both by a Bourdon type recorder and by variable-resistance pressure pickups where outputs were recorded on an oscillograph. Calibrations indicated a probable error of approximately ±3 pounds per square inch for each method. Propellant feed pressures were measured by variable-resistance pickups with a probable error of approximately ±2 pounds per square inch.

Copper-constantan thermocouples were used to measure propellant temperatures in the flow lines and at the engine cooling-jacket exit within ±1.5° F.

The oxidant tank was suspended from a calibrated strain gage to measure the weight of the contents. The content weight was determined within ±2 percent.

PROCEDURE

Propellant Preparation

Fuel and silicone oil were mixed to give a 1 percent silicone concentration. The mixture was then pumped into the tank. Liquid oxygen was transferred from a storage tank to the cell tank, which was surrounded by a liquid nitrogen bath. Fluorine-oxygen mixtures were prepared by loading first a known weight of oxygen, then adding enough fluorine to make a 15 percent mixture (by weight). Gaseous fluorine was condensed by passing it through the oxygen from the bottom of the tank. Helium was then bubbled through the oxidant to ensure complete mixing.

Engine Operation

JP-4 and oxygen were ignited in the following manner. First, a preliminary flow of propane and gaseous oxygen, introduced through the main flow lines into the engine, was ignited by an external torch. Low propellant flows (10 to 25 percent of full thrust flows) were then introduced and ignited by the propane-oxygen flame in the chamber. When the low-flow combustion stabilized, flows were increased to full-thrust values.

In starting with fluorine mixtures, low flows (approx. 10 percent of full-thrust flows) of fuel and oxidant were introduced into the chamber. These ignited spontaneously. When the low-flow combustion stabilized, flows were increased to full-thrust values. A slight fuel lead was used with both oxidants.

Most runs were of approximately 4-second duration. However, runs of 20-second and 13-second duration were made with the 15 percent fluorine mixture. 3695

RESULTS

Experimental results are presented in tables II and III and figures 3 to 6.

Specific Impulse

Figure 3 shows specific impulse for oxygen and JP-4. The maximum value was 243 pound-seconds per pound at an oxidant-fuel ratio of 2.1. This is approximately 92 percent of the theoretical peak for equilibrium composition expansion. The specific impulse obtained with 15 percent fluorine - 85 percent oxygen and JP-4 is given in figure 4. A peak specific impulse of 251 pound-seconds per pound, or approximately 92 percent of the theoretical maximum, was obtained at an oxidant-fuel ratio of 2.45. A comparison of the two showing a 3.3-percent increase with fluorine added is given in figure 5.

Heat Rejection

Figure 6 shows the heat rejection obtained at this laboratory with 15 percent fluorine - 85 percent oxygen and JP-4, which was 0.56 Btu/(sq in.)(sec) at peak impulse. Also given are the heat-rejection curves obtained by the manufacturer with oxygen - jet fuel and oxygen - ethyl alcohol. Heat rejection with 15 percent fluorine was approximately 24 percent higher than the 0.45 Btu/(sq in.)(sec) obtained by the manufacturer with oxygen - jet fuel. However, regenerative cooling was still successful in a range of oxidant-fuel ratios from 2.09 to 2.59. Note that the heat rejection obtained with 15 percent fluorine was less than that with oxygen and alcohol.

DISCUSSION

The increase in specific impulse obtained by adding 15 percent fluorine is relatively small (3.3 percent). However, for a long-range missile, this may result in a substantial increase in range. A small increase in specific impulse would be particularly beneficial in the case where a developed missile engine falls short of the performance required for full range.

Also of interest are two other advantages gained with fluorine. The bulk propellant specific gravity is increased from 1.02 to 1.06. Furthermore, the propellant combination is self-igniting with the addition of 15 percent fluorine and requires no separate ignition source.

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However, disadvantages are also incurred with the addition of fluorine. One might be propellant cost, although this is relatively minor with only 15 percent fluorine added. More important, heat rejection increases rapidly with fluorine addition. A 24-percent increase over that obtained with oxygen - jet fuel was obtained with the addition of 15 percent fluorine. Although this increase is considerable, this study shows that it can be handled successfully by a regeneratively cooled engine that was designed for alcohol and oxygen.

Material durability is important in the consideration of missile reliability. Fluorine is very damaging to organic materials such as would be used for seals and bearings. However, the relatively low percentage used in these tests had little effect on the equipment used. A Teflon seat in the oxidant fire valve eroded slowly so that after approximately 73 seconds of running with 15 percent fluorine, it began to leak slightly. Teflon bearings in the oxidant flowmeter were evidently intact after the testing. Calibrations made before and after testing showed the flowmeter to still be reliable.

The thrust chamber, made of mild steel, withstood the testing well. The following table gives a chronological summary of the testing and engine condition:

Propellants	Runs per set	Total running time per set, sec	Accumulated running time, sec (a)	Engine condition after testing
JP-4 and oxygen	17 at 4 sec each	68	68	Good
JP-4 and 15 percent fluorine 85 percent oxygen	10 at 4 sec each	40	108	Good
	1 at 20 sec	20	128	Good
	1 at 13 sec	13	141	Gouges in chamber because of oxidant impingement on wall due to hole plugging
JP-4 and oxygen	10 at 4 sec each	40	181	Good[b]
JP-4 and 15 percent fluorine 85 percent oxygen	1 at approx. 1 sec	1	182	Burn-out in vicinity of previous damage within 1 sec of full-thrust operation

[a]Does not include previous running by manufacturer.

[b]Chamber gouges had been welded and machined to original contour and the injector cleaned and backflushed before further testing.

Runs of 20- and 13-second duration with 15 percent fluorine showed the ability of the engine to cool adequately under steady-state conditions. The burn-out occurred in the range found to be safe in the previous testing. Evidently, cooling at the repaired portion of the chamber was inadequate with fluorine addition, although sufficient for oxygen alone with JP-4.

Two distinct levels of characteristic velocity were measured for oxygen - JP-4, although a single level was obtained for specific impulse. The discrepancy seemed to be in chamber pressure measurement. It is believed that either an anomaly in the chamber pressure measuring system or 3695 an effect due to the high velocity of the working fluid in the cylindrical portion of the engine led to this difficulty. The latter effect is discussed in reference 5 and is shown to increase as chamber-throat area ratio decreases. For a chamber-throat area ratio of 1.5 as used in this investigation, a deviation of 10 percent from the true chamber pressure is possible. Fluctuations in the position of the flame front with respect to the chamber pressure tap might have accounted for differences in fluid velocity and recorded chamber pressure. No values for characteristic velocity or thrust coefficient are given, since the true level for each is uncertain.

In summary, the addition of a relatively low percentage of fluorine would appear to be a promising and quite feasible method of improving the performance of current oxygen - jet fuel thrust chambers. Additional work is needed to determine if other engine parts such as the oxidant pump and valves can be used without major modification.

SUMMARY OF RESULTS

The effect of adding 15 percent fluorine to oxygen when used with JP-4 was evaluated experimentally with a commercial regeneratively cooled 5000-pound-thrust rocket engine operated at a chamber pressure of 350 pounds per square inch absolute. Results are as follows:

1. The maximum specific impulse obtained with oxygen - JP-4 was increased 3.3 percent by adding fluorine to the oxygen. The peak without fluorine was 243 pound-seconds per pound at an oxidant-fuel ratio of 2.1. The peak with fluorine was 251 pound-seconds per pound at an oxidant-fuel ratio of 2.45. The performance obtained with each combination was approximately 92 percent of its theoretical maximum for equilibrium expansion.

2. Regenerative cooling with 15 percent fluorine - 85 percent oxygen and JP-4 was successfully accomplished in a range of oxidant-fuel ratios from 2.09 to 2.59. The heat rejection at peak impulse was 0.56

Btu/(sq in.)(sec) with the fluorine addition, an increase of 24 percent over the 0.45 obtained without fluorine.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, May 2, 1955

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5. Van De Verg, Nathaniel, and De Vorkin, Howard: An Investigation of the Influence of Rocket-Chamber Configuration on Performance. Prog. Rep. No. 1-82, Jet Prop. Lab., C.I.T., June 4, 1952. (Power Plant Lab. Proj. MX801, Contract W535-ac-20260, Air Materiel Command, Contract DA-04-475-Ord 18, Dept. Army, Ord. Corps.)

TABLE I. - PROPERTIES OF JP-4

Fuel Properties	
Distillation A.S.T.M. D86-52, °F	
Initial boiling point	138
Percentage evaporated	
5	207
10	249
20	295
30	317
40	331
50	345
60	357
70	371
80	391
90	422
95	448
Final boiling point	480
Residue, percent	1.0
Loss, percent	1.0
Reid vapor pressure, lb/sq in.	2.3
Hydrogen-carbon ratio	.168
Heat of combustion, Btu/lb	18,675
Specific gravity, 60°/60° F	.779
Gravity, °A.P.I.	50.2
Aniline point, °F	139.3

TABLE II. - SUMMARY OF PERFORMANCE OF LIQUID OXYGEN AND JP-4

Oxidant-fuel weight ratio	Total propellant flow, lb/sec	Thrust, lb	Specific impulse, lb-sec/lb	Heat rejection, Btu/(sq in.)(sec)	Combustion-chamber pressure, lb/sq in. abs
1.81	21.74	5190	238	-----	348
1.86	22.43	5490	244	-----	364
1.86	19.86	4830	243	-----	345
1.91	21.93	5290	241	-----	356
1.94	20.48	4980	243	-----	356
1.94	21.23	5170	244	-----	367
1.95	22.08	5360	242	-----	357
1.96	22.03	5370	244	-----	354
1.98	22.04	5450	247	0.356	373
2.01	20.96	5130	245	-----	359
2.02	21.98	5280	240	-----	354
2.07	22.70	5570	245	.386	---
2.07	22.33	5370	240	-----	361
2.09	22.18	5330	241	-----	354
2.10	21.27	5110	240	-----	359
2.11	21.52	5280	246	.289	367
2.11	21.87	5360	245	-----	361
2.13	21.04	5060	240	-----	359
2.13	20.91	5050	241	-----	359
2.14	22.36	5460	244	-----	380
2.15	20.14	4960	246	-----	340
2.24	19.75	4790	242	-----	339
2.26	20.79	5000	240	-----	359
2.33	20.58	5020	244	-----	355
2.33	20.63	4990	242	-----	351
2.36	22.30	5320	238	-----	361
2.54	20.77	4925	238	-----	347

TABLE III. - SUMMARY OF PERFORMANCE OF 15 PERCENT

FLUORINE - 85 PERCENT OXYGEN AND JP-4

Oxidant-fuel weight ratio	Total propellant flow, lb/sec	Thrust, lb	Specific impulse, lb-sec/lb	Heat rejection, Btu/(sq in.)(sec)	Combustion-chamber pressure, lb/sq in. abs
2.09	21.04	4925	234	0.536	337
2.14	21.49	5510	256	.483	367
2.17	21.33	5305	249	.476	357
2.25	21.51	5350	249	.616	360
2.26	21.36	5330	250	.557	352
2.27	21.23	5230	246	----	348
2.30	21.61	5430	251	.536	359
2.32	21.26	5060	238	.564	340
2.36	21.53	5350	248	.638	360
2.37	21.40	5340	250	.469	359
2.46	21.48	5430	253	.645	366
2.49	21.26	5305	250	.538	359
2.59	21.16	5220	247	.568	350

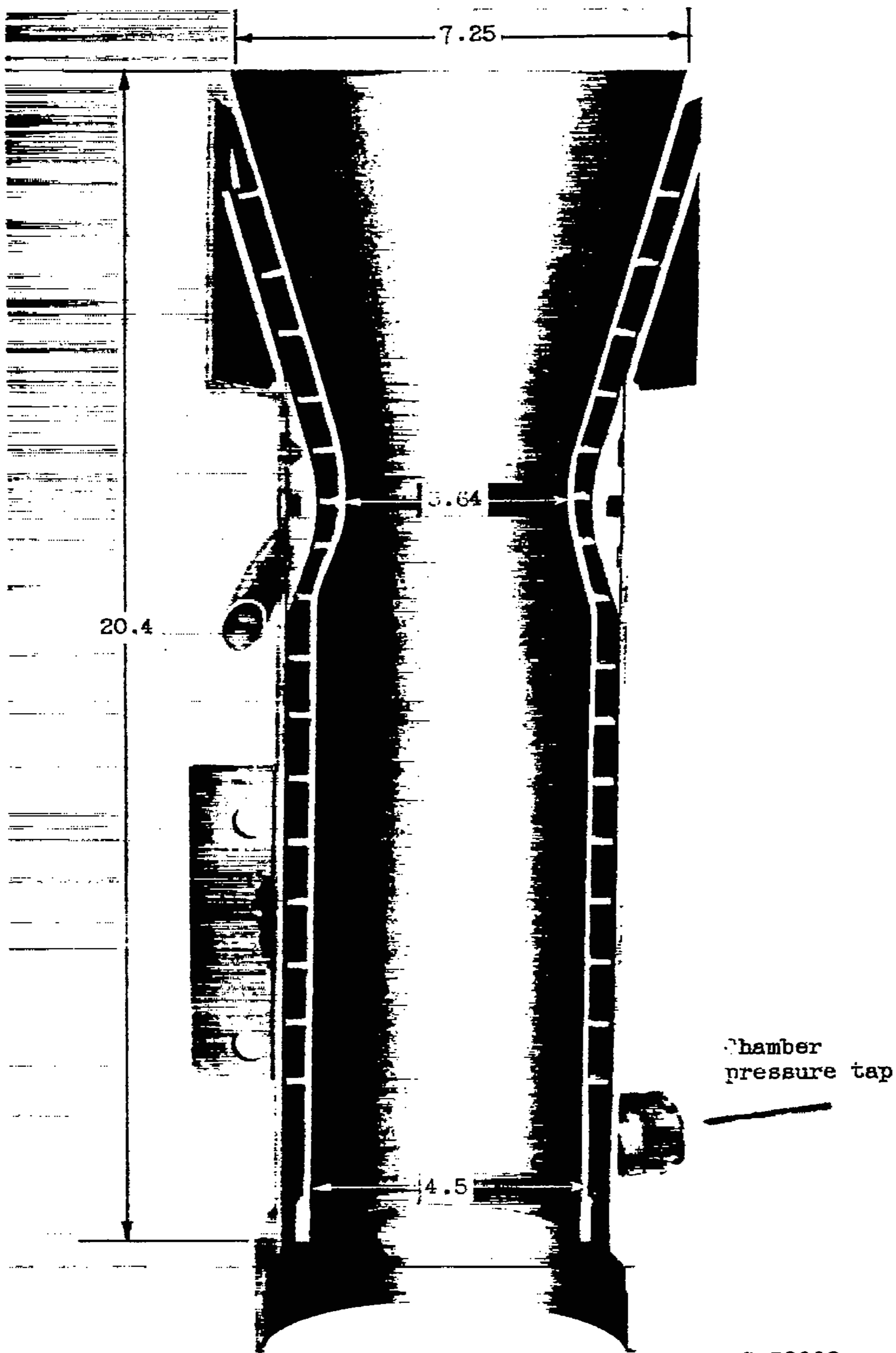

Figure 1. - 5000-Pound-thrust chamber. (All dimensions in inches.)

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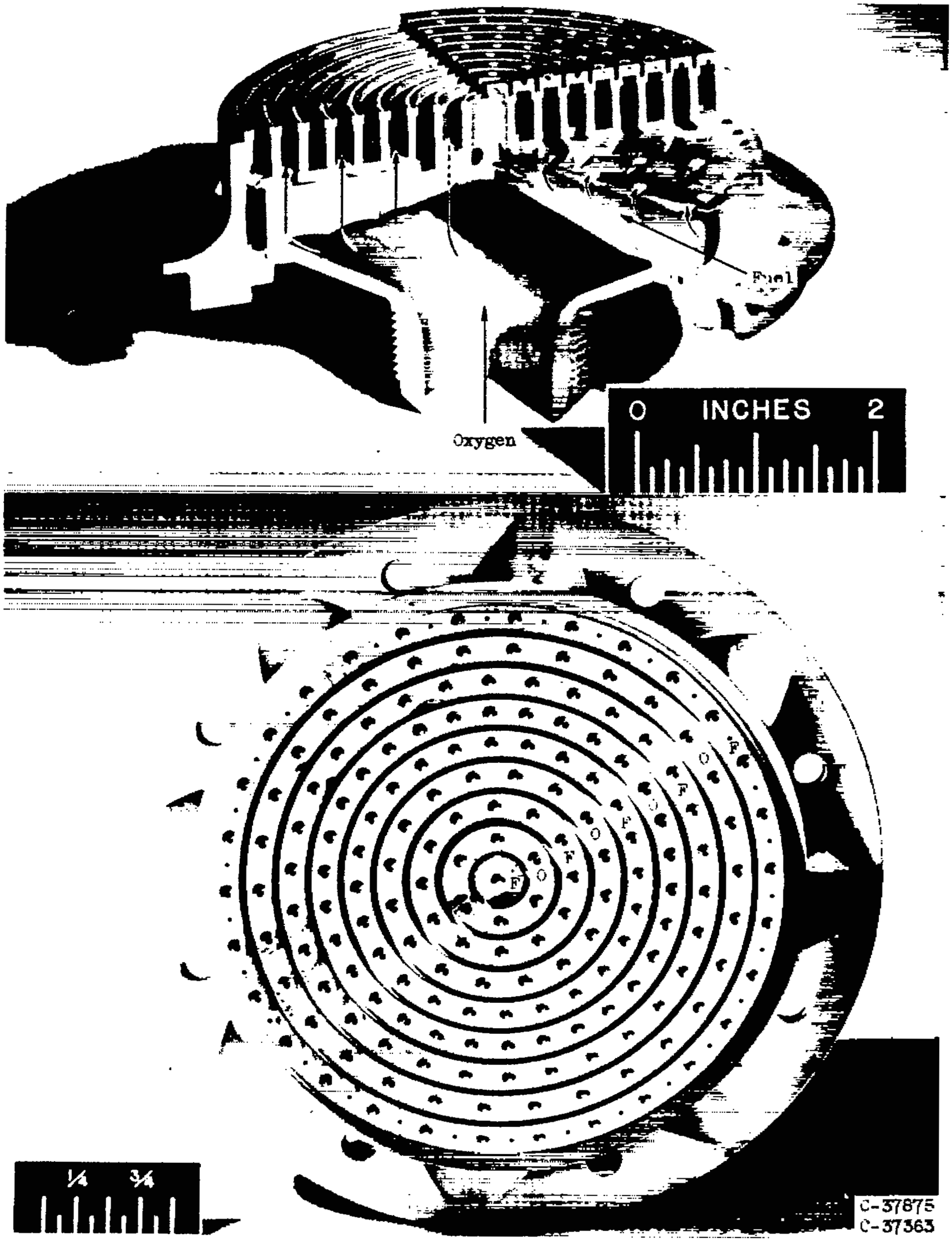

Figure 2. - 5000-Pound-thrust like-on-like injector.

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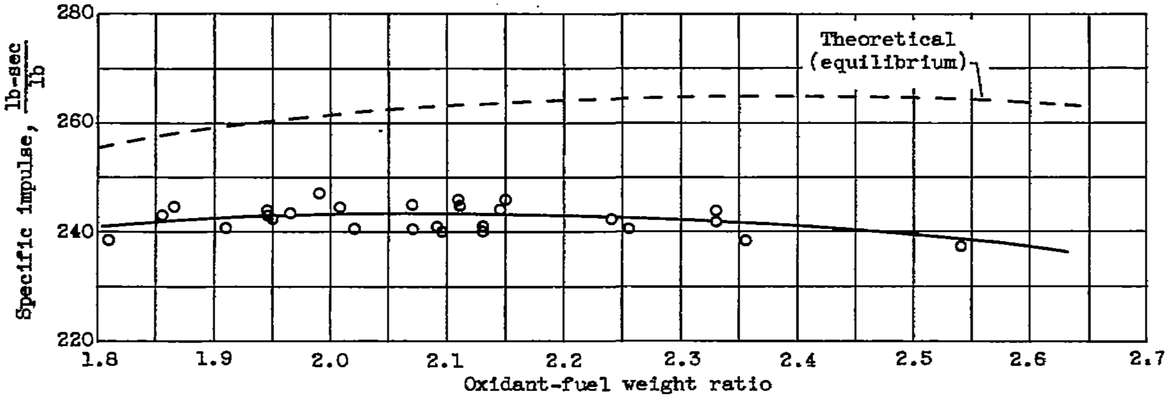

Figure 3. - Theoretical and experimental performance of JP-4 and liquid oxygen in 5000-pound-thrust engine at chamber pressure of 350 pounds per square inch absolute.

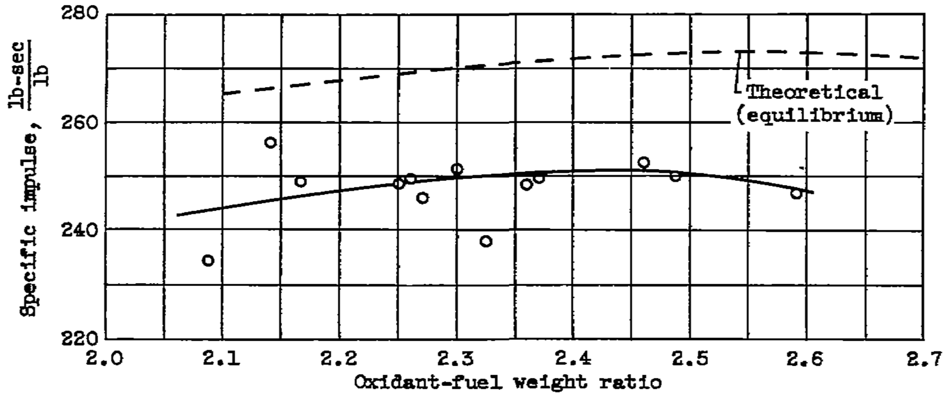

Figure 4. - Theoretical and experimental performance of JP-4 and 15 percent fluorine - 85 percent oxygen in 5000-pound-thrust engine at chamber pressure of 350 pounds per square inch absolute.

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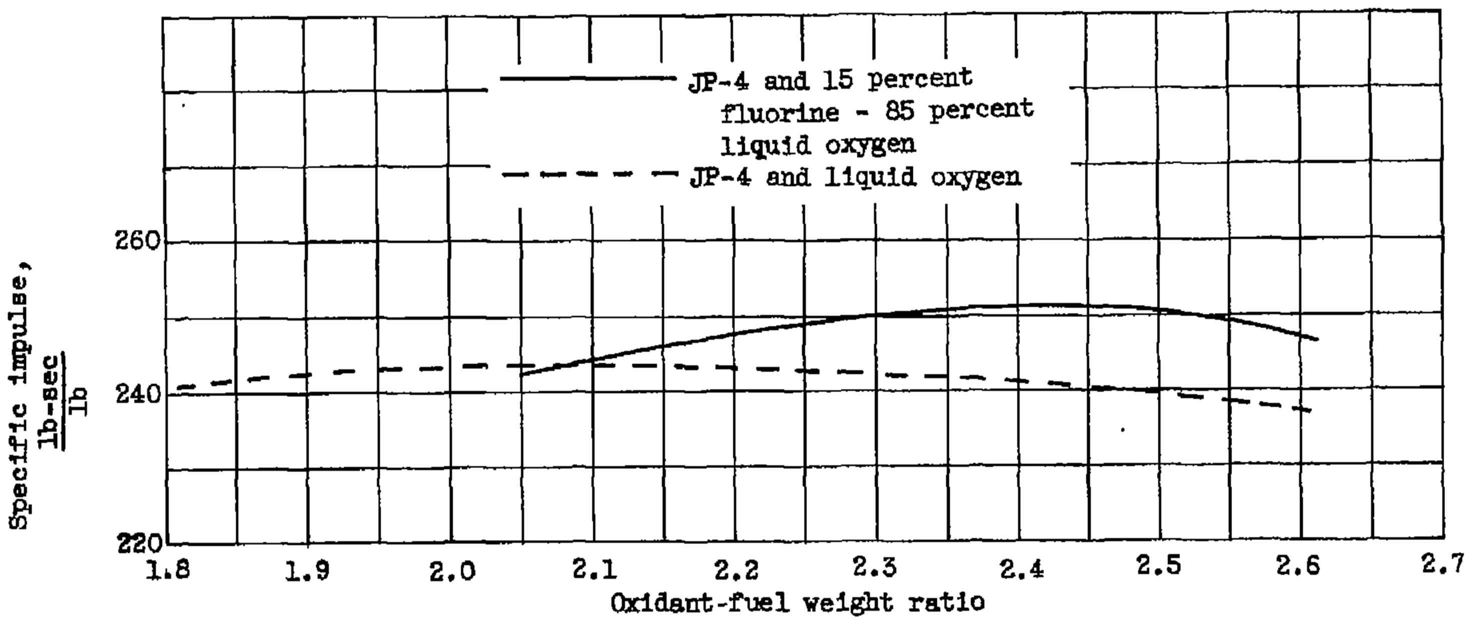

Figure 5. - Comparison of performance of JP-4 and liquid oxygen with JP-4 and 15 percent fluorine - 85 percent oxygen in 5000-pound-thrust engine at chamber pressure of 350 pounds per square inch absolute.

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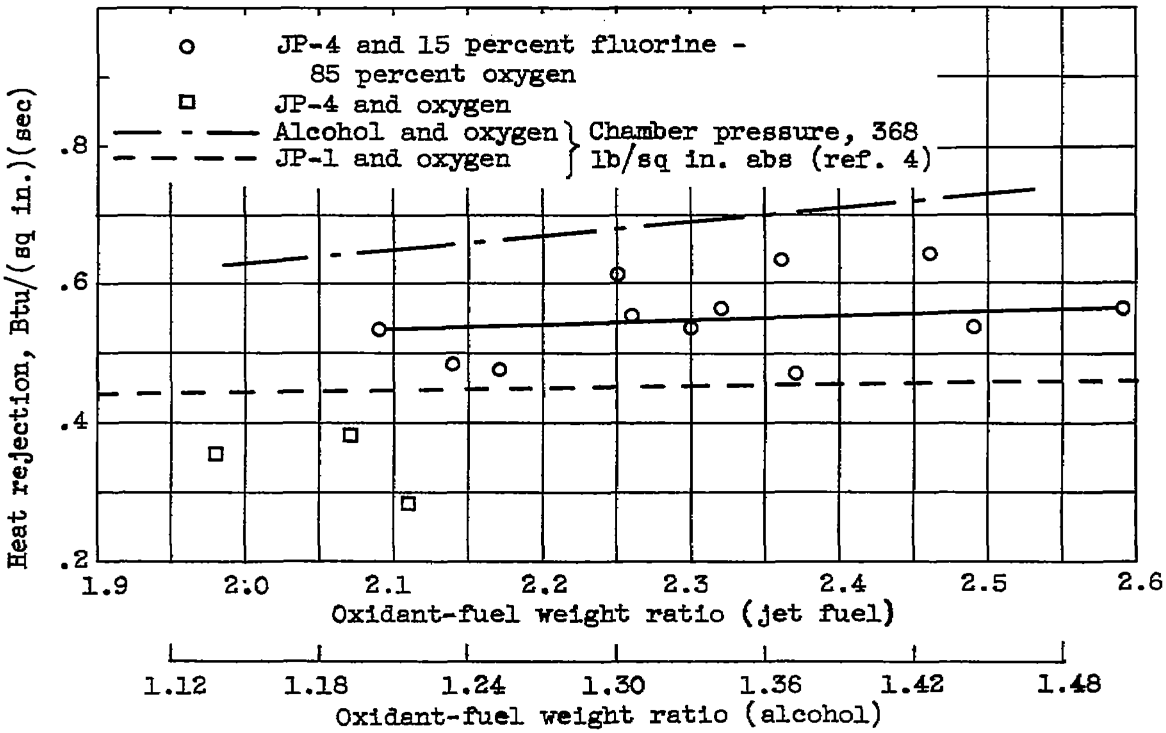

Figure 6. - Heat-rejection rates for 15 percent fluorine - 85 percent oxygen with JP-4 and for oxygen with several fuels.

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